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200-μm *ISO* observations of NGC 6946: evidence for an extended distribution of cold dust

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ABSTRACT

We have used the *Infrared Space Observatory* (*ISO*) to obtain a resolved 200-μm image of the nearby spiral galaxy NGC 6946. We compare these observations with those made at 60 and 100 μm by the *Infrared Astronomical Satellite* (*IRAS*). Whereas *IRAS* mainly detected warm dust ($T \approx 30$ K) heated by star-forming regions, *ISO* detects an extended distribution of cold dust ($T \leq 22$ K) that is heated by the general interstellar radiation field. The *IRAS* emission tends to follow the molecular gas while it appears that the colder dust has a stronger association with atomic hydrogen. The cold dust is more extended in the radial direction than the optical, near-infrared, *IRAS* and radio continuum (20 cm) emission. The total gas-to-dust mass ratio is found to be ≈290. This is much closer to the Galactic value of ≈160 than the value of 1240 found using *IRAS* data only.

Key words: dust, extinction – galaxies: individual: NGC 6946 – galaxies: ISM– infrared: galaxies.

1 INTRODUCTION

Observations of the Universe at previously unavailable wavelengths have almost always revealed the unexpected. *IRAS* provided us with a first look at the extragalactic Universe at far-infrared wavelengths (12–100 μm), locating numerous sources amongst the diffuse emission from our own Galaxy. The relatively large far-infrared outputs of many of these galaxies was a surprise (Rieke & Lebofsky 1986; Soifer Heuck & Neugebauer 1987). We now know that there are galaxies that emit as much as 99 per cent of their bolometric luminosity in the far-infrared (Sanders et al. 1988) and even a ‘typical’ galaxy like ours emits about half of its total energy at far-infrared wavelengths (Davies et al. 1997). The major source of the far-infrared emission is the absorption of stellar light by classical dust grains (radius ≈0.1 μm) which reemit the incident energy at longer wavelengths. Since a large fraction of the stellar output is reprocessed through absorbing dust, the role dust plays in influencing our perceptions of galaxies has reached a new importance (see Davies & Burstein 1995 and Block 1996 for reviews).

After considering the *IRAS* observations it became clear to us (Disney, Davies & Phillipps 1989) that far-infrared measurements with $\lambda < 100$ μm may only (however new and revealing) be touching the top of ‘a far-infrared iceberg’. A grain immersed in a ‘typical’ interstellar radiation field ($T_{\mathrm{eff}} \approx 10^4$ K, dilution $W \approx 10^{-14}$, emissivity $\beta = 1$, see Disney et al. 1989) will have a temperature of $T_{\mathrm{d}} \approx T_{\mathrm{eff}} W^{1/(4-\beta)} \approx 15$ K. The peak in the emission spectrum will then occur at

$$\lambda_{\mathrm{m}} \approx \frac{2900}{T_{\mathrm{d}}}\left(\frac{5}{5+\beta}\right) = 161\ \mu\mathrm{m}$$

for $\beta = 1$(138 μm for $\beta = 2$). Thus we might expect the bulk of galactic dust to be radiating predominately at wavelengths longer than those detectable by *IRAS*. At larger radial distances we would expect the dilution factor to be smaller and hence the emission peak to be shifted even further away from the *IRAS* 100-μm data point. Typical dust temperatures derived using *IRAS* data are ≈30 K (Devereux & Young 1990), higher than the above prediction and at variance with recent measurements of the dust temperature within our Galaxy. The temperature of the diffuse dust in the Galaxy has recently been determined by Reach et al. (1995) using the FIRAS instrument on *COBE*. They find little change in temperature with direction observed away from the Galactic plane, with typical values being 17–18 K.

If the emission beyond 100 μm is dominated by cold dust (Sodroski et al. 1994; Reach et al. 1995) then, because of the $T^{(4+\beta)}$ factor, a large fraction of the dust mass in galaxies may have been previously undetected. Sodroski et al. (1994) show [using *COBE* (DIRBE) data for our Galaxy] that 60–75 per cent of the far-infrared luminosity (in the Galactic plane) comes from cold (17–22 K) dust associated with diffuse H I clouds, 15–30 per cent from cold (≈19 K) dust in molecular clouds and less than 10 per cent from warm ≈29 K dust in extended low-density H II regions.

The debate over the relative amounts of dust that are hot, warm and cold has been part of a broader discussion on the predominant mechanisms heating the dust (see Devereux 1995 for a review). Controversy has raged over whether the dust is heated in the main by hot young stars – and so the far-infrared emission is a good indicator of star formation or whether the dust is diffuse and more likely to be heated by the general interstellar radiation field. Our view is that we expect both to be true – it depends on the wavelength of observation. At $\lambda < 100\,\mu$m we would expect the emission to be dominated by warm and hot dust associated primarily with star-forming regions, but that at $\lambda > 100\,\mu$m we would expect to increasingly find the signature of a colder component heated by the general interstellar radiation field (Eales, Wynn-Williams & Duncan 1989). Observations longward of 100 μm, as described in this paper, are a crucial test of this hypothesis.

Although the far-infrared luminosity may not arise predominately in star-forming regions, the gas-to-dust mass ratio is a measure of the star formation history of a galaxy, in the sense that it reflects the conversion of gas into heavy elements (Eales & Edmunds 1996). If galaxies have converted similar fractions of their gas into stars then one would expect (given similar stellar mass functions and time-scales) that they would have similar gas-to-dust mass ratios. Gas-to-dust mass ratios determined using *IRAS* data give values of between 400–2000 for other spiral galaxies (Devereux & Young 1990) while for our Galaxy the corresponding ratio (derived using observations beyond 100 μm) is about 160 (Sodroski et al. 1994). Either other spiral galaxies have very different star-forming histories or their dust masses have been previously underestimated.

In this paper we describe *ISO* (ISOPHOT) 200-μm observations of the nearby spiral NGC 6946 and compare this data with that obtained by *IRAS*.

2 OBSERVATIONS

NGC 6946 is a nearby Sc galaxy viewed at an inclination of $i = 31°$. We will assume a distance of 10.1 Mpc to the object (Engargiola 1991). It is thought to have active star formation throughout its disc and a mild star burst at the centre (Tacconi & Young 1990). The optical images were obtained using the 2048^2 T2KA CCD camera mounted on the Kitt Peak 0.9-m telescope; this gives a 23-arcmin field of view. The near-infrared data were obtained with the Wyoming IR telescope and were constructed from a mosaic of four 4.8-arcmin frames. The optical and near-infrared data reduction are fully described in Trewhella (1997). Calibrated *IRAS* HiRES images, with a resolution of ≈100 arcsec, were obtained from IPAC. Observations at 200 μm were obtained from the *Infrared Space Observatory* (*ISO*) during 1996 October. Data were collected using the ISOPHOT instrument (Lemke et al. 1996) in a P32 mapping mode. The sampling along the in-scan and cross-scan directions was 31 and 93 arcsec respectively.

Reduction of the *ISO* data was carried out using the ISOPHOT interactive analysis software package (PIA V6.0). This corrects for non-linearity in the ISOPHOT detectors and applies a deglitching algorithm to remove the effects of cosmic rays. Measurements of an internal source (the fine calibration source) allows the signal on the detectors to be converted into MJ sr^{-1}. This measurement is carried out both before and after mapping the object so as to monitor any changes in the detector responsivity.

The absolute calibration of the ISOPHOT instrument is still subject to some uncertainty and so we have compared our data with observations carried out with other instruments. Engargiola (1991) has mapped the central 5 arcmin of NGC 6946 at 200 μm using the Kuiper Airborne Observatory (KAO) and has derived a total flux of 226 ± 45 Jy for this region. Although our data is of poorer resolution (which tends to smooth out the brightest regions of the galaxy) we obtain a higher value of 270 ± 23 Jy. The two agree within the stated errors. The error in the above value comes essentially from the accuracy with which we can determine the sky background ($+/-$ 11 MJy sr^{-1}). The random pixel-to-pixel errors are of the order of 0.4 MJy sr^{-1}. We have also compared the 'sky background' recorded in the *ISO* map with values expected on the basis of *IRAS* survey measurements. The 100-μm 'sky' emission near NGC 6946 is about 15 MJy sr^{-1}. Reach et al. (1995) have shown, using 100 μm-2 mm data collected by the FIRAS instrument on *COBE*, that foreground dust at this galactic latitude is well described by a 19 K blackbody modified by a $\gamma = 1.5$ emissivity law. On this basis we would expect ≈29 MJ sr^{-1} for the 200-μm background. We actually measure ≈40 MJ sr^{-1}. There is a possibility that the present calibration may overestimate the flux by ≈30 per cent.

Fig. 1 shows the *ISO* 200-μm image compared to a *B*-band image of NGC 6946 and a contour plot of the *IRAS* 100-μm data.

3 RESULTS

In order to compare emission at different wavelengths, we have removed bright stars from the optical and near-infrared images and then convolved them along with the *IRAS* data to the same resolution as the *ISO* 200-μm observations. The *ISO* beam is somewhat broader than the theoretical Airy profile and has been approximated by a 117 arcsec (FWHM) Gaussian (Tuffs et al. 1996). Fig. 2 shows this approximation along with recently acquired mapping measurements of a point source. The Gaussian fit is slightly wider than the observational data and so, if anything, we might be marginally over-estimating the extent of the optical, near-infrared and *IRAS* emission compared to *ISO*.

After convolving we have used a standard galaxy photometry package to derive the azimuthly averaged radial surface brightness profiles in the optical (*BVRI*), near infrared (*K*) and far infrared (12, 25, 60, 100 and 200 μm), see Fig. 3. The profiles have been normalized to the same value at 30 arcsec (one *ISO* pixel radius) so that the relative fall in surface brightness can be compared – the result of this type of comparison is independent of the absolute calibration of the data (see below). In Table 1 we list the derived exponential scalelengths obtained from fitting the profiles between 100 and 250 arcsec. For the optical, near-infrared and *IRAS* data the errors arise primarily from uncertainty in the smoothing required to convolve to the same resolution as *ISO*. At 200 μm, errors in the scalelength arise primarily from uncertainty in the sky subtraction.

NGC 6946 shows a clear colour gradient in $(B - K)$ to the limit of the *K*-band data (becomes bluer with radius). Whether this is as a result of dust or changes in stellar population/metallicity is still controversial (de Jong 1995). The *K*-band surface brightness follows more closely the *IRAS* data than any of the other optical bands. If one assumes that the *K*-band observations are essentially extinction free (Block 1996) then there appears to be a close association between the warm dust and the underlying distribution of stars since the stellar continuum peaks in the near-infrared (Engargiola 1991). The relatively small change in separation of the *IRAS* profiles indicate an almost constant temperature across the disc for hot and warm dust consistent with inferences made by other authors (Devereux 1995). The *ISO* 200-μm data indicate that there is an increasing contribution from cold dust as the radial distance increases. Since any temperature gradient (warmer in the centre) would make the observed profile steeper, for a given surface density of dust, the true surface density must fall off more slowly than the stars (as measured in any of the optical or near-infrared bands) – the cold dust is more extended than the stars in the radial direction. We have compared the *ISO* profile along in-scan and cross-scan directions and the result does not appear to be a result of any transient effects in the instruments detectors.

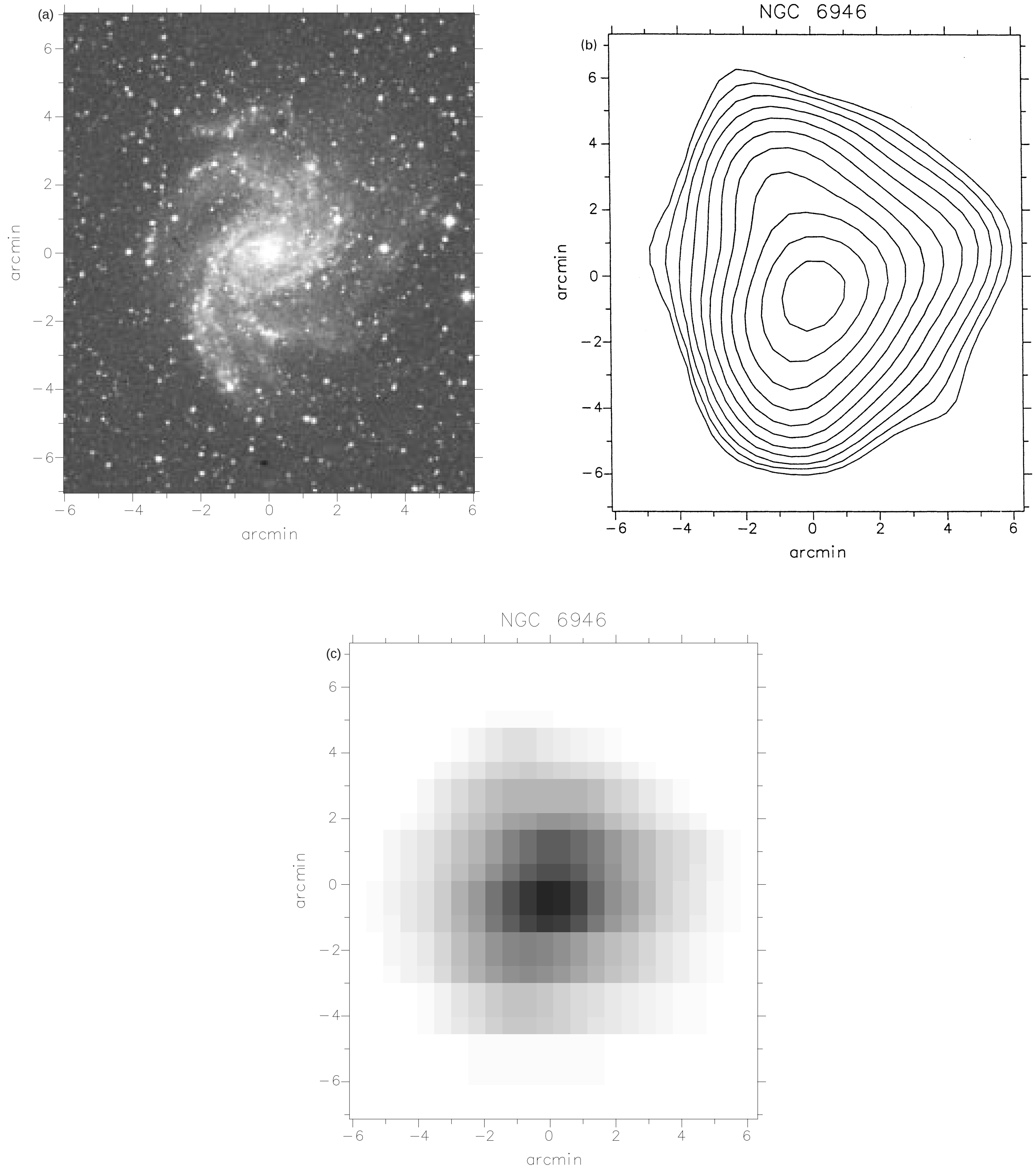

Figure 1. NGC 6946 at various wavelengths. Each image has the same scale and orientation. (a) *B* band. (b) Contour plot of the *IRAS* 100-μm data smoothed to the same resolution as the *ISO* data. The contours start at 3σ and then increase by 0.5 mag in surface brightness. (c) *ISO* 200-μm data. The maximum surface brightness corresponds to 250 MJy sr^{-1}.

At first sight this result appears to contradict the extensive observations of NGC 6946 made by Engargiola (1991). He observed NGC 6946 with the KAO at 100, 160 and 200 μm and concluded that the scalelength of the far-infrared emission was in fact shorter than that of the optical emission (we approximately agree on the *R*-band scalelengths). Although he finds, like us, that the scalelength in the far-infrared increases with wavelength, his 200-μm data only extend to 150 arcsec from the galaxy centre. He does not use an azimuthally averaged profile as we have used, but rather separate apertures at different positions and, moreoever, it is clear from his fig. 3(b) that there is large scatter in the points furthest from the galactic centre and they are predominately higher than the

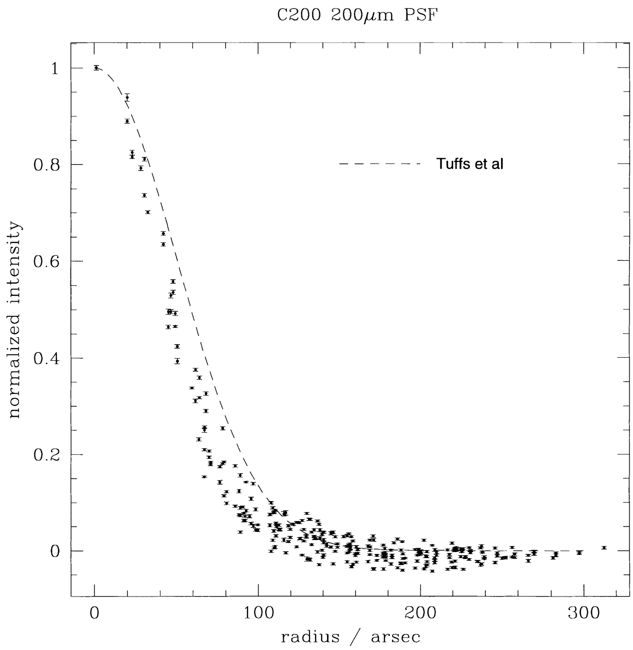

Figure 2. The *ISO* 200-μm point spread function. The data points are from an image of NGC 7027 observed by the ISOPHOT consortium using PHT32 mapping mode. The dashed line is the Gaussian fit given by Tuffs et al. (1996).

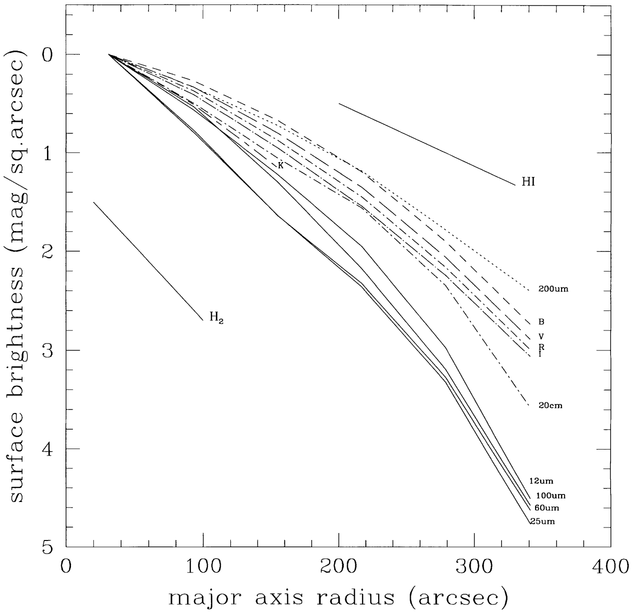

Figure 3. The radial surface brightness profiles at various wavelengths. The data have been normalized at 30 arcsec from the galactic centre and each wavelength has been convolved with a Gaussian to match the resolution of the *ISO* 200-μm data. Random errors on each point are <0.01 mag. but systematic errors arise from the uncertainty in convolving the optical, near-infrared and *IRAS* data. This introduces a 4 per cent error in the derived scalelengths. At 200 μm the background uncertainty leads to an error of 10 per cent in the derived scalelength. The lines marked H_2 and H I indicate the change in column density with radius as measured by Tacconi & Young (1986).

best-fitting line. Is this an indication that the profile, if traced to greater distances, would become much flatter – in agreement with our observations?

It is clear that there is a good correlation between far-infrared emission and gas column density in our Galaxy (see for example Davies et al. 1997 and references therein). Tacconi & Young (1990) have measured both the molecular and atomic hydrogen column density for NGC 6946 as a function of radius. The molecular hydrogen peaks at the centre and then falls with an exponential scalelength of ≈90 arcsec. The H I has a dip at the centre, peaks at ≈184 arcsec and then falls with a scalelength of ≈300 arcsec. H I and H_2 contribute approximately equally to the surface density at about 200 arcsec (see their fig. 6). The emission detected by *IRAS* closely follows the H_2 column density. Could it be that the 200-μm emission is starting to be influenced by dust associated with the much more extensive atomic gas? If so the 200-μm profile should flatten further at larger galactic centre distances. The H I is detectable out of some 600 arcsec at a column density of 20×10^{20} atom cm^{-2} which is ≈1/5 of its value at the edge of our 200-μm profile.

The global correlation between the 20-cm radio continuum and the *IRAS* luminosity (Dickey & Salpeter 1984) has been used as an argument in favour of the *IRAS* luminosity originating in star-forming regions. They argue that the radio continuum is produced by synchrotron radiation with the injection rate of particles from supernova being proportional to the star formation rate. An alternative explanation is that the continuum emission is just a reflection of the density of interstellar material (Evans 1992). The luminosity in synchrotron radiation is proportional to the product of the number density of relativistic electrons (n) and $B^{1-\alpha}$ where B is the magnetic field strength and α is the synchrotron spectral index. For $n \propto \rho(\mathrm{ISM})$ and $B \propto \rho(\mathrm{ISM})^{1/2}$ (Mouschovias, Shu & Woodward 1974) and a spectral index of -1 (Evans 1992) the continuum emission scales as $\rho(\mathrm{ISM})^2$ [ρ(ISM) is the density of the interstellar medium]. The far-infrared emission is proportional to the product of the stellar density and the dust density (Disney et al. 1989) which, if both are proportional to ρ(ISM), leads again to the far-infrared emission being proportional to $\rho(\mathrm{ISM})^2$. In either case the prediction is that the emission detected by *IRAS* and the radio continuum emission should closely follow each other but, the far-infrared luminosity does not necessarily relate directly to star formation activity. Our radial profiles clearly indicate that the ratio of radio continuum emission to 60–100 μm emission increases radially. This behaviour has been confirmed by Lu et al. (1997) using *ISO* 60-μm data. Their explanation is that the cosmic rays diffuse to greater distances than the photons that heat the dust, giving rise to a more diffuse radio emission. This interpretation requires that both the far-infrared emission ($\lambda < 100$ μm) and the radio continuum

Table 1. Derived exponential scalelengths.

Wavelength	Scalelength (arcsec)
B	141 ± 6
V	130 ± 5
R	124 ± 5
I	120 ± 5
K	102 ± 4
12 μm	98 ± 4
25 μm	88 ± 4
60 μm	90 ± 4
100 μm	86 ± 4
200 μm	160 ± 16

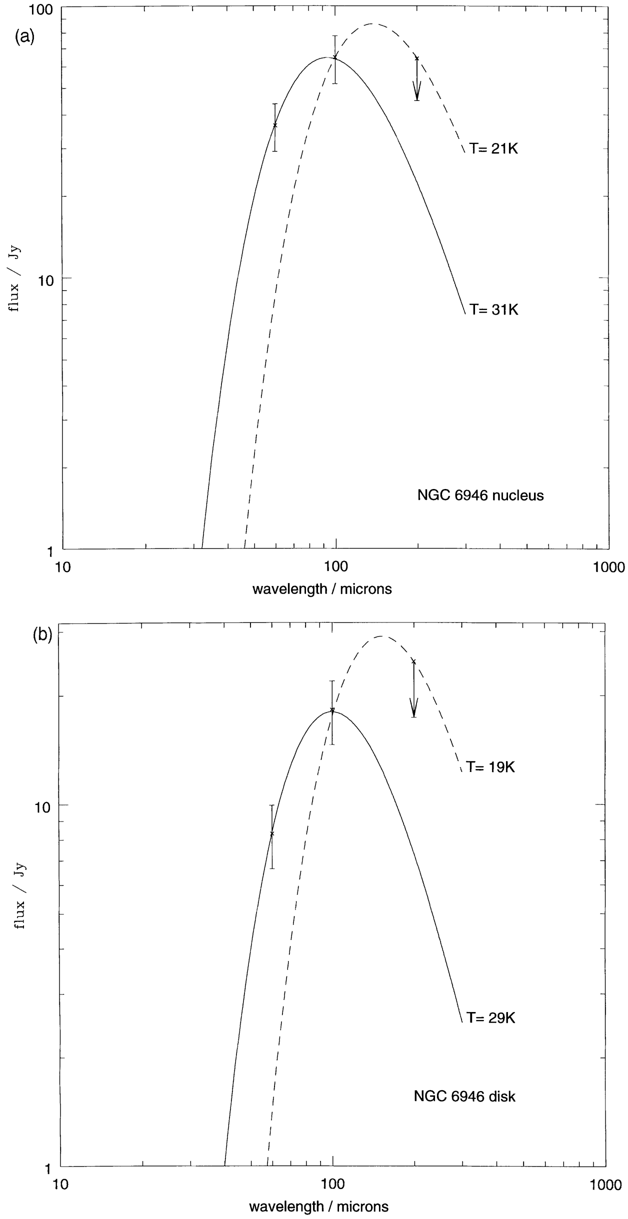

Figure 4. The measured flux at 60- and 100-μm (*IRAS*) and at 200-μm (*ISO*). (a) Within a $117 \times 117\,\mathrm{arcsec}^2$ resolution element at the galactic centre. (b) Within a $117 \times 117\,\mathrm{arcsec}^2$ resolution element 3 arcmin from the galactic centre. The effect of a 30 per cent overestimate of the *ISO* 200-μm flux is indicated by the arrow.

emission trace star formation activity. Since the ratio of radio continuum emission to *ISO* 200-μm emission decreases radially then the emission detected by *ISO* clearly does not relate to recent star formation if the argument proposed by Lu et al. (1997) is correct.

As we have both *IRAS* and *ISO* calibrated data we can also make a quantitative measurement of how the *ISO* data affect the determination of the dust temperature and mass (Fig. 4). Although the dust will certainly have a range of temperatures the simplest assumption is that the data can be fitted by a single blackbody curve modified by a power-law emissivity of index β. There is no single curve that provides a good fit to both the *IRAS* 60- and 100-μm points and the *ISO* 200-μm point, but we can fit to the two *IRAS* points and then to the *IRAS* 100-μm and *ISO* 200-μm points. This provides us with an estimate of how the *ISO* data have revised our perceptions of dust mass and temperature (see also Devereux 1995). These estimates may in turn need to be revised once good submm observations become available, although existing observations indicate that the major dust mass component has a temperature of about 20 K (Chini 1996).

The fits to the far-infrared spectral energy distribution are shown in Fig. 4. Fig. 4(a) is for the nucleus and Fig. 4(b) is for a point 3 arcmin from the centre of the galaxy. We have derived dust masses using the dust emissivity of Hildebrand (1983). The derived masses and temperatures at the above positions (within a $117 \times 117\,\mathrm{arcsec}^2$ resolution element) are given in Table 2. It is clear that by just using the *IRAS* observations the dust temperature is overestimate by $\approx$10 K and the dust mass is underestimated by a factor of 4–10 in each resolution element. Similar conclusions have been reached by Engargiola (1991) and Smith, Harper & Loewenstein (1984) who both make measurements longward of the *IRAS* filters. The dust temperature of about 20 K compares well with the value determined for our Galaxy using *COBE* (*FIRAS*) data (Reach et al. 1995).

Using the central dust mass density (Table 2) and the exponential scalelength (Table 1) we can integrate beyond the observed region to derive a total dust mass of $\approx 10^6\,\mathrm{M}_\odot$ using the *IRAS* data and $\approx 10^8\,\mathrm{M}_\odot$ when we use the *ISO* data. If we assumed that the dust is smoothly distributed we could derive the surface density as a function of position and hence the optical depth. It is also possible to derive the extinction if we were to assume a model of how the stars are distributed relative to the dust. We have not done this because it is quite clear from an analysis of the $(B-K)$ colour map that the dust is somewhat clumpy and so the optical depth and extinction will vary even for points at the same radial distance from the centre. Trewhella (1997) discusses the optical depth and extinction as a function of position.

Table 2. Derived masses and temperatures.

	Nucleus		Disc	
	IRAS	*ISO*	*IRAS*	*ISO*
Mass ($\mathrm{M}_\odot$) $\gamma = 1$ in a $117 \times 117\,\mathrm{arcsec}^2$ aperture	1.6×10^6	7.4×10^6	6.4×10^5	3.8×10^6
Mass ($\mathrm{M}_\odot$) $\gamma = 2$ in a $117 \times 117\,\mathrm{arcsec}^2$ aperture	9.4×10^5	8.2×10^6	3.6×10^5	4.2×10^6
Temperature K ($\beta = 1$)	37	27	34	24
Temperature K ($\beta = 2$)	31	21	29	19

Devereux & Young (1990) give a total gas mass for NGC 6946 of $\approx 3 \times 10^{10}$ $M_{\odot}$ and a gas-to-dust mass (derived from the *IRAS* data) ratio of 1240 within the optical radius. Using the above gas mass and the dust mass determined using the *ISO* data we derive a total gas-to-dust ratio of 290. This value is much closer to the Galactic value ($\approx$160) than that determined using *IRAS* data only.

4 CONCLUSIONS

Previous determinations of the dust temperature in other galaxies using data from *IRAS* have indicated dust temperatures of about 30 K (Alton et al. 1998). Along with the apparent correlation of far-infrared luminosity with indicators of star formation this has led to the view that far-infrared luminosity is a good measure of star-forming activity in galaxies. We have shown that observations at wavelengths longer than about 100 μm indicate the presence of cold dust ($\approx$20 K) heated by the general interstellar radiation field and possibly associated with the diffuse atomic hydrogen. The cold dust component is more extended in the radial direction than the observed distribution of stars. At each point in the galaxy the cold dust mass is 4–10 times larger than that detected using *IRAS* data only. The total mass associated with the cold component gives a gas-to-dust mass ratio that is much closer to the accepted value for our Galaxy.

This extended distribution of cold dust indicates the presence of metals at large distances from the galactic centre and may also indicate the presence of cold molecular material. Gerhard & Silk (1996) have recently proposed that an extended cold gas component could explain the flat rotation curves of galaxies. Although we have insufficient data to relate dust emission directly to molecular material at large radial distances, there are two important consequences of an extended dust distribution with regard to the interpretation of galaxy rotation curves. First, dust absorption tends to flatten the observed radial distribution of light compared to the underlying distribution of the stars (Davies 1990). Secondly, if the cold dust is tracing a cold gas component then the mass-to-light ratio is increasing with radius. Both of the above will affect the maximum disc modelling of rotation curves and the inference off missing mass.

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